Use of Line Surge Arresters Coupling With Underbuilt Ground Wire to Improve the Lightning Performance of 220kV Overhead Transmission Lines

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ABSTRACT

Lightning protection systems have been installed on transmission lines (TL), but lightning still causes a considerable number of failures. In this regard, new lightning protection solutions are necessary for TL in order to reduce power outages caused by lightning. In this paper, a method is presented to improve the lightning protection performance of TL through the use of line surge arresters (LSAs) and underbuilt ground wiring (UGW), as well as to reduce both overhead TL outage rates and LSA numbers. Research results show that using LSA and UGW on 220 kV overhead power lines can provide greater lightning protection. By adding only one UGW, the coupling factor increases to 70%, so the voltage on the insulator is reduced when lightning strikes the tower. Combined with one UGW on the 220 kV overhead power line with low grounding resistance, installing one LSA at the top phase has better lightning protection than installing two LSAs. It is particularly useful for TL management companies to improve lightning protection using the results. The electromagnetic transients in this study were simulated using EMTP/ATP.

1. INTRODUCTION

One of the most important factors, when TL is desiged, is lightning strike rates. Out rates are based on the combination of lightning strikes to the tower top or midspan, as well as strikes directly to the phase conductors. LSA has been used to boost lightning protection on TL, as documented in IEEE Std 1243-1997 [1]. It is difficult to improve lightning protection performance if only one TL is used. Therefore, it is necessary to develop a lightning protection solution that enhances its effectiveness.

In areas with high ground resistivity and ground lightning density, LSAs are used to reduce lightning failures on TL [2-5]. Installing one LSA on the upper phase conductors increases the lightning backflashover current threshold by 50 kA for lines rated 220 kV and 30 kA for lines rated 110 kV [4], [6]. If LSA is installed on all phase conductor of all towers, faults due to lightning strikes can be eliminated. Nevertheless, it is not feasible to install LSA in all locations due to huge investment cost. It is actually the principle of using UGW that the ground wire is installed parallel to phase wire of the line and below the lowest phase conductor. The UGW does not protect the phase conductors like the shielding wires, but it only increases coupling factor with phase conductors, therefore, it reduces the voltage on the insulations of the TL [7], [8], [9]. According to [8] the maximum coupling factor of phase can be increased up to 30% when using a UGW, so the voltage causing the discharge on the insulation is reduced, which can increase the lightning performance of the TL. As shown in [8], the voltage on the insulator of the 220 kV transmission line decreases between 19% and 32% when one UGW and two UGWs are installed. The voltage on the insulator decreases between 26 and 44 percent when lightning strikes the top of the tower. In this case, the footing grounding resistances are between 20 Ω and 80 Ω. Whenever there is a high level of soil resistivity and lightning ground flash density, this method is even more effective. Additionally, UGW will increase the coupling factor between phase conductors and dissipate part of the lightning current to neighboring towers, and lower the voltage on the insulator of a tower hit by lightning.

Neither method has its own advantages or disadvantages, the actual statistics show that not all positions were struck by lightning. Also, the intensity of the lightning current was not large enough to cause flashover. Hence, LSA doesn't need to be installed at these tower locations. As mentioned above, if all the positions are installed with LSA to eliminate lightning, the investment cost is too great. Although UGW provides easy installation and low costs, lightning performance of TL is only partially improved when lightning strikes the tops of towers or shielding wires. This method does not protect the insulators from lightning strikes when the phase conductor is directly struck.

In this paper, the study on the installation of LSA coupling with UGW of 220 kV overhead transmission lines

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is presented. The parameters of the tower, the phase conductors, shielding wires, insulations, and the footing resistance are taken from TLs in Viet Nam. Aside from that, EMTP/ATP software and electrogeometric model (EGM) were used. To begin with, a comparison is made among outage rates for shielding wire alone, shielding wire + 1 LSA, shielding wire + 2 LSAs, and shielding wire + 1 LSA + UGW. Furthermore, the correlation between the footing resistances of towers and outage rate of TL is analyzed and calculated. Choosing LSA also requires considering absorption energy and discharge current, which are vital factors to keep in mind.

2. COUPLING FACTOR AND VOLTAGE ON INSULATOR

2.1 Coupling Factor

Considering the simple case, there are two conductor wires placed in parallel to each other and parallel to the ground (Fig.1). A system of maxwell wave propagation equation is established as follows [7]:

$$\begin{aligned} V_1 &= z_1 i_1 + z_{12} i_2 \\ V_2 &= z_{12} i_1 + z_2 i_2 \end{aligned} \qquad (1)$$

Accordingly, i_1, i_2 are currents; V_1, V_2 are voltages and z_1, z_2 are surge impedances of wires 1 and 2, respectively; whereas z_{12} is their mutual surge impedance.

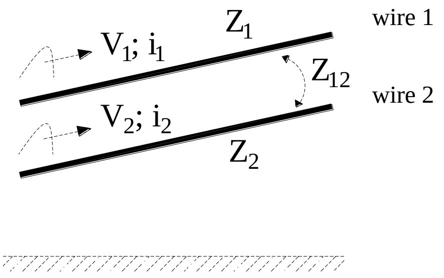


Fig. 1. Coupling factor between two wires.

The wave propagation equation (1) shows the contribution to the magnitude of the voltage on a wire consisting of 2 components:

i) The voltage on that line due to the current flowing on the line multiplied by the self-surge impedances;

ii) By virtue of the mutual surge impedance between wires 1 and 2, the induced voltage component is due to the current flowing on the other line.

As a result of [7], the coupling factor equals the ratio of the induced voltage (ii) to the voltage of the wire itself (i).

$$K = \frac{V_2}{V_1} \qquad (2)$$

Assuming that wire 1 is a phase wire, wire 2 is a shielding wire and that the current flowing on the phase wire is very small compared to the lightning current. From equations (1) and (2), the coupling factor K is defined as:

$$K = \frac{z_{12}}{z_1} \qquad (3)$$

The case of 3 wires (assuming wire 1 is shielding wire, wire 2 is a phase conductor and wire 3 is UGW) is shown in Fig. 2.

The system of equations for the propagation of Maxwell waves is determined [13]:

$$\begin{aligned} V_1 &= z_1 i_1 + z_{12} i_2 + z_{13} i_3 \\ V_2 &= z_{21} i_1 + z_2 i_2 + z_{23} i_3 \\ V_3 &= z_{31} i_1 + z_{32} i_2 + z_{33} i_3 \end{aligned} \qquad (4)$$

The lightning currents flowing on shielding wire and UGW wire are assumed to be the same and the coupling factor of shielding wire. and UGW to phase conductor wire is determined as follows (5) [7].

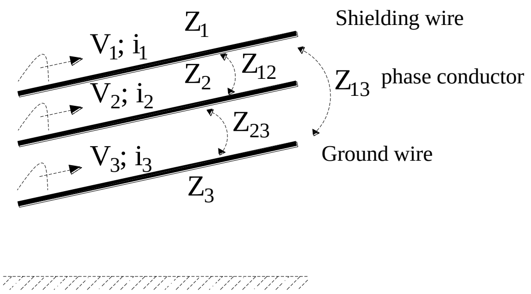


Fig. 2. Coupling factor in case of 3 wires.

$$K = \frac{z_{13} + z_{23}}{z_1 + z_{12}} \qquad (5)$$

Here, z_1, z_2, z_{12}, z_{13} are the self-surge impedances of the shielding wire, the UGW, and their mutual surge impedance. This means that the coupling factor is determined by the mutual surge impedance between the shielding wire and the UGW, as well as the shielding wire's self-surge impedance or the UGW's self-surge impedance. Also, there is a relationship between the surge impedance of a transmission line and its wire configuration (distance between the shielded wire with the UGW and its phase conductor, single-circuit or twin-circuit transmission lines, number of UGWs, shielded wire and footing resistance, etc.).

2.2 Voltage on Insulator caused by lightning

Two scenarios, in which lightning strikes tower tops, shielding wires, or directly strikes a phase conductor, are illustrated in Fig. 3. When lightning strikes directly a phase conductor, the insulation string will bear the voltage caused by the lightning current. Considering the fact that lightning current on phase conductors is split into two and runs on both sides. The lightning voltage can be calculated by multiplying half the lightning current value by the surge impedance of the phase conductor (this surge impedance is around 400 Ω). Thus, in this case, the voltage applied to the insulator does not depend on whether there is a shielding wire or a UGW.

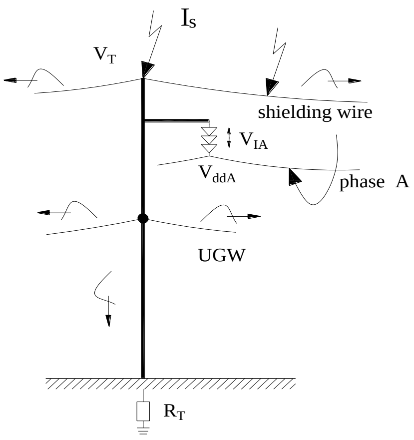


Fig. 3. Determination voltage across insulator when the lightning strike.

The voltage across insulation is determined as follows:

$$V_I = \frac{I_s.Z_{dd}}{2} + V_{lv} \tag{6}$$

According to this equation, V_I is the voltage on the insulator, I_s is the lightning current amplitude, Z_{dd} is the surge impedance of the phase conductor, and U_{lv} is the power frequency voltage of the source.

When lightning strikes to shielding wire (tower top or mid-span) with amplitude I_s, the lightning current divided in 3 different directions. The first direction is to follow the shielding wire to the neighbor tower. The second direction is to follow the tower to the ground and three is to follow the UGW to adjacent towers. It is similar to the propagation of voltage waves on shielding wire and phase conductors, voltage wave propagates on the tower is also accompanied by loss, reflection and refraction. In simple case, voltage waves reflected from adjacent towers (along shield wires) and from grounding system (along tower body) are disregarded. As only the voltage drop on the tower body is considered, the voltage drop depends on the surge impedances of the tower and shielding wire. Combined with the method of determining the coupling factor from subsection A, the voltage on the insulator of any phase (for example phase A) V_{IA} is calculated as:

$$V_{IA} = (1 - K_A)V_T \tag{7}$$

where, V_T is the voltage at the top of the tower, U_{ddA} is the voltage on phase A, and K_A is the coupling factor between UGW and phase conductor A with shielding wire.

According to IEEE Std 1243-1997 [1], the corona model on shield wire or phase conductor should be used in computation. There is little difference between the voltage across the insulator when corona is considered and when it is not considered [10]. In the corona effect, the ionizing of the air around the conductor increases the line capacitance, thereby reducing the surge impedance of the conductor is reduced. Furthermore, the voltage across the insulation is reduced. Given that we only consider the most dangerous case of voltage on insulation, our study does not take the corona effect into account. Additionally, only one phase conductor is assumed in equations 6 and 7. Using the EMTP/ATP software., the voltage on the insulator is determined by both power-frequency voltages, reflections of the voltage wave and phase angle of the power-frequency voltage.

3. THE CONSIDERED TRANSMISSION LINE

As shown in figure 4, the study is conducted on single circuit 220 kV transmission line. The phase conductor uses type ACSR 400/52 wire, the shielding wire uses type TK70, the phase conducto is divided into two bundled wires, the distance between two bundled wire is 40 cm. The length of the overpass is 350 m, the length of the TL is 100 km, ground flash density is 10 flash/km^2.yr, equivalent to 100 days of thunderstorms in a year. The parameters of TL for calculations are presented in Table 1.

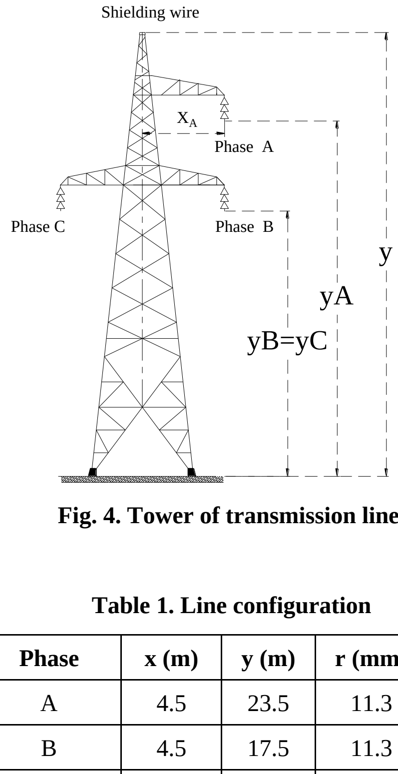


Fig. 4. Tower of transmission line.

Table 1. Line configuration

No	Phase	x (m)	y (m)	r (mm)	Sag (m)
1	A	4.5	23.5	11.3	6
2	B	4.5	17.5	11.3	6
3	C	-4.5	17.5	11.3	6
4	Shielding wire	0	28.5	4.7	5
5	UGW	0	15	4.7	5

Lightning protection for a 220 kV transmission line using shielding wire, LSAs and UGW is shown in Fig. 5. For a 220 kV tower protected by one LSA, it is installed in phase A, and if two LSAs are used, both phases are installed in phase A. The distance between the UGW and the branch phase B or phase C swing arm is d (where d is 0 m or 5 m).

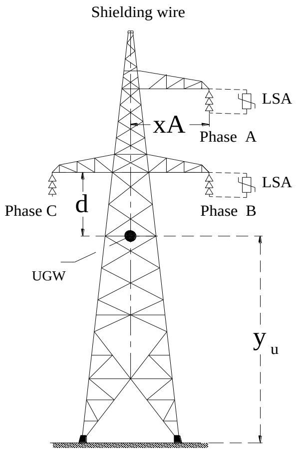


Fig. 5. Description of lightning protection solutions for 220 kV transmission line.

4. MODELLING OF 220 kV OVERHEAD TRANSMISSION LINE

4.1. Transmission Line model

Modeling the 220 kV overhead TL using J.Marti's frequency-dependent conductor parameters is reported in EMTP/ATP [11]. This model considers the mutual influence between the phase conductors, the shielding wire and the UGW.

4.2. Tower model

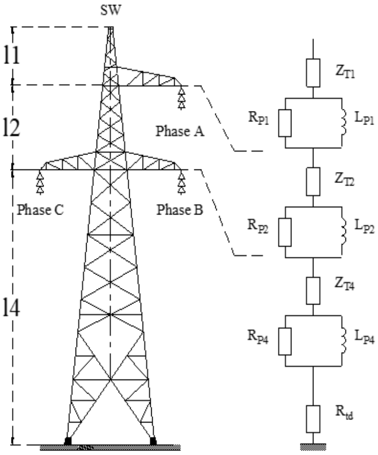
The tower is represented in EMTP/ATP by the multi-story model as described in [12]. Three segments make up the tower model: the upper, middle, and lower sections, each consisting of a wave impedance (Z_T) in series with an inductor (L_p) in parallel with a resistor (R_P). A corresponding electrical model is derived based on the following rules shown in Fig.6.

4.3. Footing resistances of towers model

The tower's resistance is set using EMTP/ATP as follows [12]:

$$R_T = \frac{R_0}{\sqrt{1+\frac{I}{I_g}}} \tag{8}$$

In this case, R_0 represents the DC resistance at low frequency (Ω); *I* is the lightning current through the footing resistance of the tower (kA); I_g is the minimum lightning current through the grounding resistor to cause earth ionization (kA). The minimum lightning current I_g is determined as follows [12].



$Z_{T1} = Z_{T2} = 220\ \Omega$
$Z_{T4} = 150\ \Omega$
$\gamma = 0,8944$
$\tau = 2H/v$
$r_{T1} = -2\times Z_{T1}\times \ln\gamma/(l_1+l_2)$
$r_{T2} = -2\times Z_{T4}\times \ln\gamma/(l_4)$
$R_{P1} = r_{T1}\times l_1 = 22.34\ \Omega$
$R_{P2} = r_{T1}\times l_2 = 26.78\ \Omega$
$R_{P4} = r_{T2}\times l_4 = 33.48\ \Omega$
$L_{P1} = R_{P1}\times\tau = 4.24$ mH
$L_{P2} = R_{P2}\times\tau = 5.09$ mH
$L_{P4} = R_{P4}\times\tau = 6.36$ Mh
$H=y=28.5$ m
$v=3.10^8$ m/s

Fig. 6. Multistory tower model.

$$I_g = \frac{E_0\rho}{2\pi R_0^2} \tag{9}$$

where: E_0 is the soil ionization, with a value of 400 kV/m [12]; ρ is the soil resistivity (Ωm); R_0 ranges from 10 Ω to 50 Ω.

4.4. Line insulators flashover model

The insulation flashover voltage can be calculated using equation (3) during simulation and compared with the actual insulation voltage by the IEEE model in [13].

$$V(t) = 400.L + \frac{710}{t^{0.75}}.L \tag{9}$$

here, *V(t)* is flashover strength (kV), *t* is time to flashover (s), and *L* is gap or insulator length (m). Throughout this paper, the length of the insulator is given as 2.19 m and the discharge gap is given as 1,8 m.

4.5. Line arrester model

Figure.7 shows the voltage-current (V-I) characteristic of the LSA based on IEEE model [14].

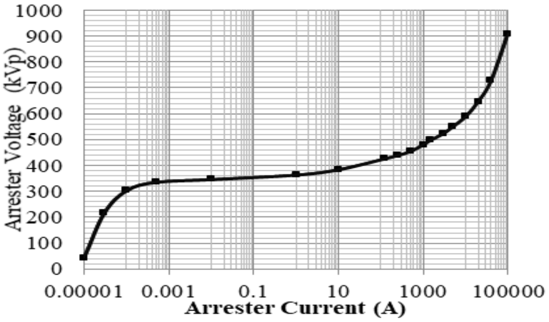


Fig. 7. Voltage - Current characteristic of the LSA.

5. OUTAGE RATE OF TRANSMISSION LINE

Outage rate of transmission line (T_{FR}) is total flashover rates including the backflashover rates (*BFOR*) and the shielding failure flashover rates (*SFFOR*) [7].

$$T_{FR} = BFOR + SFFOR \tag{10}$$

5.1 BackFlashover Rates (BFOR)

The method of determining the *BFR* of TL is presented in [7]. The main formulas to determine *BFR* are presented as follows:

$$BFOR = 0.6N(G).P(I>I_c) \tag{11}$$

with *N(G)* is the number of strokes to line (flashes/100km.yr) and is estimated by [7]:

$$N(G) = N_g.\left(\frac{28H^{0.6}+S_g}{10}\right) \tag{12}$$

Where: H is the tower's height in meters (m), S_g is the distance between the shielding wires horizontally (m), and N_g is the ground flux density. This paper uses $H = 28.8$ (m), $S_g = 0$ (m), and $N_g = 10$ (flashes/km^2.yr)

P(I$_c$) represents the probability of the current exceeding *I*. A probability distribution of current peak values can determined as (13).

$$P(I > I_C) = \frac{1}{1+\left(\frac{I}{31}\right)^{2.6}} \tag{13}$$

In this case, I_C is the threshold lightning current that causes flashovers on the insulator when lightning strokes to the top of the towe or span.

4.6. Shielding Failure Flashover Rate (SFFOR)

Using an electric geometry model, shielding failure flashover rate is calculated. Equation 14 [1] determines the lightning attraction distance *r(I)* based on the lightning current.

$$r(I) = AI^b \tag{14}$$

Lightning striking shielding wire or phase conductor has $A = 10$ and $b = 0.65$, while lightning striking the earth has $A = 3.6+1.7\ln(43\text{-}y)$ or $A = 5.5$, where y is the height of the phase conductor and $b = 0.65$.

Figure 8 illustrates an electrical model of a transmission line with two shielding wires. A lightning strike on a tower or shielding wire is called D_g strike, whereas lightning strike on a phase conductor is called D_c strike. The shielding failure flashover was calculated using the method given in [1] determined according to the formula 15.

$$SFFOR = 2N_g L \int_{I_{min}}^{I_{max}} D_c(I).f(I)dI \tag{15}$$

In this equation, L represents the length of the transmission line (km), whereas D_c is determined from the electrogeometric model. A shielding wire-phase conductor diagram is shown in Fig. 9, which shows one side of the diagram presented in Fig. 8.

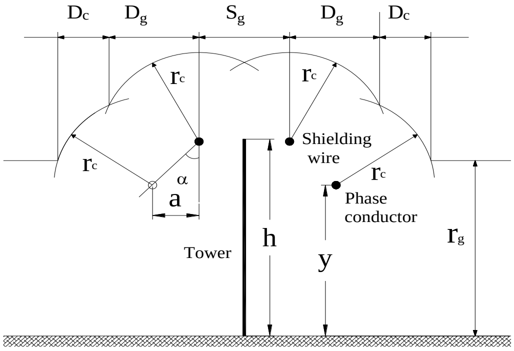


Fig. 8. The electrogeometric model, definitions of distances [7].

The angle between the two radii r$_c$ is defined as β:

$$\beta = \sin^{-1}\left(\frac{(h-y)\sqrt{1+\tan^2(\alpha)}}{2r_c}\right) \tag{16}$$

The angles θ and α are calculated as:

$$\theta = \sin^{-1}\frac{r_g-y}{r_c}, \quad \alpha = \tan^{-1}\frac{a}{h-y} \tag{17}$$

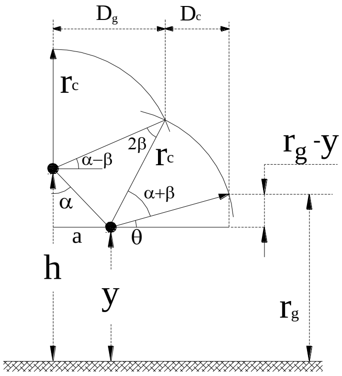


Fig. 9. Expanded view of Fig. 8 [21].

From this Fig.9:

$$D_c = r_c\left[\cos(\theta)-\cos(\alpha+\beta)\right] \tag{18}$$

The probability density of lightning current *f(I)* can be calculated as [1]:

$$f(I) = \frac{1}{\sqrt{2\pi}\sigma I}e^{-\frac{(\ln I/I_M)^2}{2\sigma^2}} \tag{19}$$

where, I_M is the median value of lightning current and σ is the logarithmic standard deviation, according to [1]:

$I < 20\text{kA}, I_M = 61.1\text{kA}, \sigma = 1.33$
$I > 20\text{kA}, I_M = 33.31\text{kA}, \sigma = 0.605$

The minimum lightning current Imin, which strikes directly the phase conductor, causes a discharge on the insulator string, can be determined as

$$I_{min} = \frac{2U_{50\%}}{Z_c} \tag{20}$$

$U_{50\%}$: lightning impulse critical flashovers kV, Z_c: is the surge impedance of the phase wire. I_m is the maximum lightning current striking to the phase conductor, according to [7] determined as follows: the current increases, r_c and r_g increases and the D_c decrease.

When the current increases to Im then D_c is zero, the Maximum value rgm of r_g is calculated as:

$$r_{gm} = \frac{(h+y)/2}{1-\gamma\sin(\alpha)}; \ \gamma = \frac{r_c}{r_g} \tag{21}$$

So, I_{max} estimated by equation:

$$I_{max} = \left[\frac{r_{gm}}{A}\right] e^{\frac{1}{b}} \tag{22}$$

6. SIMULATION RESULTS

6.1 Voltage on insulator

If lightning strikes the tower's top or directly to the phase conductor, the overvoltage on the insulator string is determined by the tower's footing resistance. Simulation with the case of lightning current 30 kA (1.2/50 µs, slope-ramp waveform), the grounding resistance of tower is 10, 20 and 30 Ω respectively, voltage waveform on the insulator string of phase A when lightning strikes to tower top presented in Fig.10.

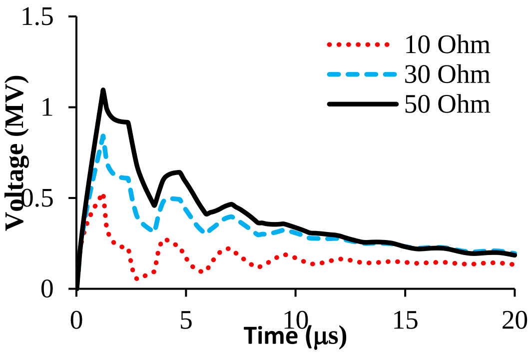


Fig. 10. Voltage on the insulator of phase A when lightning strikes the tower top, the lightning current is 30kA (1.2/50 µs).

According to simulations, reducing the tower's resistance will reduce the voltage on the insulator chain during lightning strikes. Reduce grounding resistance of tower from 50 Ω to 30 Ω reducing the voltage across the insulator string from 1150 kV to 860 kV and resistance of tower is 10 Ω then the voltage across the insulator string to only 550 kV. Therefore, reducing resistance of tower will increase the lightning protection of the power transmission line.

6.2 Coupling Factor when using UGW

Simulation for lightning current (1,2/50µs, slope-ramp waveform) strikes to tower top with configuration shown in Fig.4. The result of compare the coupling factor of the phase conductor with the case of single shielding wire and with the case of adding one UGW (with distance d = 0m and d = 5m) are shown in Fig. 11. The coupling factor *K* of phase conductor A increases by 35% and the coupling factor *K* of phase conductor B or phase conductor C increases to 70% in compare with the case using only a single shielding wire. The installation of UGW will reduce the voltage on the insulator, contributing to improving the efficiency of lightning protection for the power transmission line.

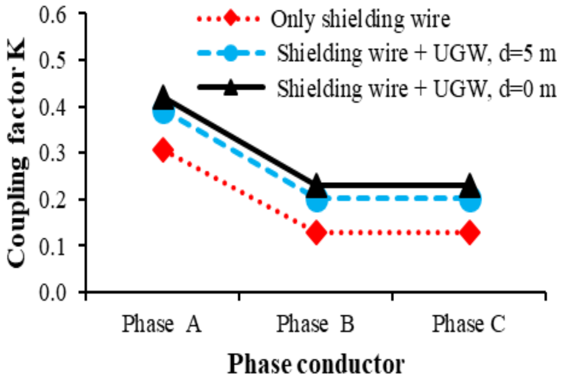
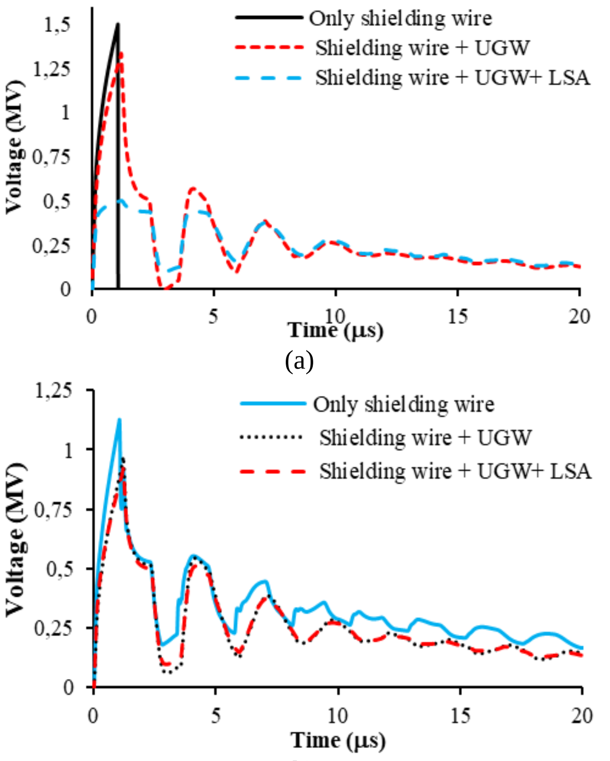


Fig. 11. Coupling factor of phases with shielding wire and UGW.

6.3 Voltage on insulator when using UGW

Figure 12 shows the simulation results of the voltage waveform on the insulation of phases A, B, and C when lightning strikes the top of the tower at 90 kA. For a stricken tower, the grounding resistace of tower is 10 Ω in three different cases: case 1 only one shielding wire; case two one shielding wire coupling with one UGW; case three one shielding wire coupling with one UGW and one LSA installed on phase A (with d = 0 m).

In the case of using only shielding wire, flashover occurs on the insulation of phase A, while using shielding wire coupling with UGW no flashover on the insulation of phase A. In case using shielding wire coupling with UGW and installation of LSA on phase A, the maximum voltage across on the insulator of this phase is equal to the residual voltage of LSA, so there is no flashover (Fig. 12.a). The insulator of phase B and phase C do not flashover in all 3 cases (Fig. 12.b). The maximum voltage value on the insulation of phase B or phase C in case using shielding wire coupling with UGW is reduced by 1.2 times compared to the case using only shielding wire. As a result of using UGW, TLs will be more lightning resistant.



(a)

(b)

Fig. 12. Voltage on the insulation of phase A (a) and phase B (b)

6.4 The Outage rate of Transmission line

Simulation for a single circuit 220 kV line with the configuration shown in Fig. 4 with the following cases: using only a single shielding wire; using shielding wire coupling with UGW; using a single shielding wire with installation 2 LSAs at phase A and phase B and case using a single shielding wire coupling with UGW and installation one LSA at phase A for the footing resistances from 10 Ω to 50 Ω. Simulation results and calculation of line fault rates caused by lightning according to the cases are presented in Fig.13.

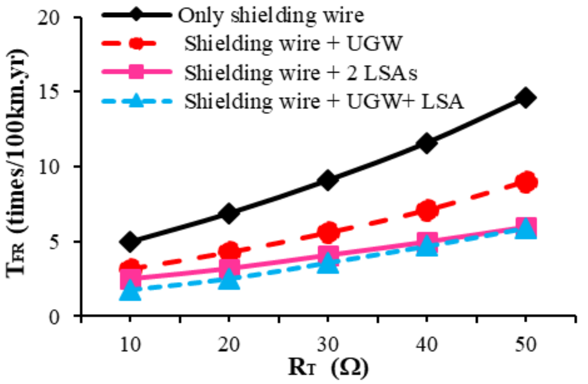


Fig. 13. Outage rate of transmission line with different cases according the tower footing resistance.

The simulation results show that by using shielding wire coupling with UGW and installation LSA at phase A, the outage rate of TL decreases compared to using only a single shielding wire or using shielding wire coupling with UGW. On the other hand, using one shielding wire coupling with UGW and installation one LSA at phase A can provide better protection than one shielding and installation two LSAs at phase A and phase B.

Figure.13 also shows that when the footing resistance is 50Ω, the outage rate of the TL in case using shielding wire coupling with UGW and installation one LSA is reduced by 1.5 times compared with case using shielding wire coupling with UGW and decreased by 2.4 times compared to using only shielding wire. The simulation results also show that the outage rate of TL with the proposed method is equivalent to reducing the footing resistances from 50 Ω to 15 Ω when using shielding wire coupling with UGW and reducing the footing resistances from 50 Ω to 30 Ω if using only shielding wire. Noted that it is very difficult to reduce footing resistances, especially for the TL cross high soil resistivity areas. The outage rate of TL according the tower footing resistance in Table 2.

Table 2. The flashover rate of transmission line with different cases according the tower footing resistance

R_T (Ω)	Case 1 (SW)	Case 2 (SW+UGW)	Case 3 (SW+ 2 LSAs)	Case 4 (SW+LSA+ UGW)
Shielding Failure Flashover Rate (flash/100km/yr)				
10	0.3	0.3	0.19	0.21
20	0.3	0.3	0.19	0.21
30	0.3	0.3	0.19	0.21
40	0.3	0.3	0.19	0.21
50	0.3	0.3	0.19	0.21
Backflashover Rate (flash/100km/yr)				
10	4.7	2.9	2.3	1.6
20	6.6	4.0	3.0	2.3
30	8.8	5.3	3.9	3.4
40	11.3	6.8	4.8	4.5
50	14.3	8.7	5.8	5.7
Total Flashover Rate (flash/100km/yr)				
10	5.0	3.2	2.5	1.8
20	6.9	4.3	3.2	2.5
30	9.1	5.6	4.1	3.6
40	11.6	7.1	5.0	4.7
50	14.6	9.0	6.0	5.9

During the simulation, two LSAs are connected at phases A and B, and one LSA is coupled with one UGW at phase A when lightning strikes the top of the tower with a tower grounding resistance ranging from 10 Ω to 50 Ω. The minimum lightning current (I_c) causing BFOR is shown in Fig.14. The results show that when the tower grounding resistance range of less than 40 Ω, using one LSA coupling with one UGW provides better lightning protection than using two LSAs. When the tower grounding resistance increases (R_T > 40 Ω) using two LSAs provides higher lightning protection efficiency than using one LSA coupling with one UGW.

Figure. 15 show that the method using shielding wire coupling with UGW and installed LSA at phase A, the BFOR of line is smaller than the case of installed two LSAs. With the footing resistance is 10Ω, use one LSA on phase A and coupling with UGW the critical backflash current increases from 116 kA to approximately 140 kA, equivalent to the BFOR of line due to lightning strike to the tower top or mid-span of shielding wire reduced to 1.4 time (from 2.2 times/100 km.yr to 1.5 times/100 km.yr).

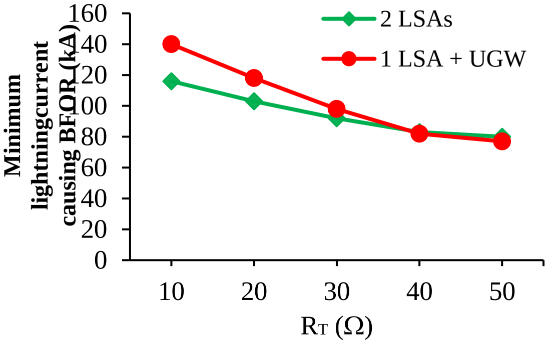


Fig. 14. Efficency of different lightning protection.

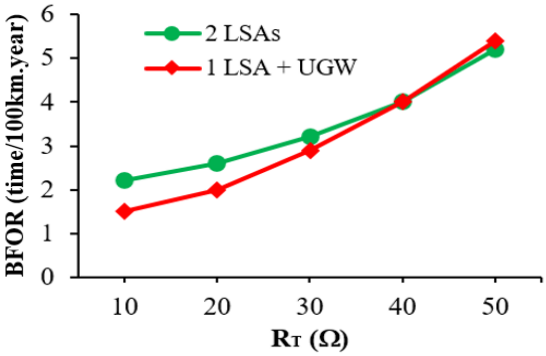


Fig. 15. The BFR of the transmission line when using two LSAs and when using one LSA coupling with UGW.

This simulation result has proven the effectiveness of the solution using adding UGW coupling with one LSA comparing to the case of using two LSAs. The minimum lightning current causing discharge on the first insulator chain when lightning hit to tower top shown in Fig.14 in the case of installed 2 LSAs at phase A and phase B (SW+2 LSAs) and case of installed 1 LSA at phase A and 1 UGW (SW+LSA+UGW) when the tower footing resistance is 10 Ω, next determine the BFR are presented in table 3.

Table 3. Sum of shielding failure flashover rate and backflashover rate

Case	Phase A	Phase B	Phase C
Only shelding wire			
Only shelding wire, R_T = 10 Ω			
Critical stroke current required for flashover without operating voltage (kA)	83	135	135
Average value of critical stroke current required for flashover with operating voltage (kA)	79.5	121	121
Probability that stroke current axceeding average critical value	0.080	0.028	0.028
Back flashover rate for each phase BFR (number/100km/yr)	**4.768**	1.755	1.755
Back flashover rate for all the line (number/yr/100km)	8.278		
Installed 2 LSAs at phase A and phase B (SW+ 2 LSAs)			
Only shelding wire +2 LSAs (A-B), R_T=10 Ω	A	B	C
Critical stroke current required for flashover without operating voltage (kA)	--	--	139.5
Average value of critical stroke current required for flashover with operating voltage (kA)	--	--	116.5
Probability that stroke current axceeding average critical value	0	0	0.031
Back flashover rate for each phase BFR (number/yr/100km)	0	0	**2.158**
Back flashover rate for all the line (number/year/100km)	2.158		
Installed 1 LSA at phase A and 1 UGW (SW+ LSA+UGW)			
Only shelding wire+1 LSA (A)+UGW, R_T=10 Ω	A	B	C
Critical stroke current required for flashover without operating voltage (kA)	--	159.5	159.5
Average value of critical stroke current required for flashover with operating voltage (kA)	--	140.0	140.0
Probability that stroke current axceeding average critical value	0	0.019	0.019
Back flashover rate for each phase BFR (number/yr/100km)	0	**1.229**	1.229
Back flashover rate for all the line (number/yr/100km)	2.458		

6.5 Energy Absorption of LSA

Simulation with lightning current 90 kA (1.2/50μs) strike the tower top, the footing resistance is 10Ω. It is lightning current threshold that makes the LSA in phase A to operate, while the other phases are not installed LSA to do not discharge. The simulation result determines the absorbed energy of LSA in the case of using shielding wire with LSA and the case of using shielding wire with LSA coupling with UGW is shown in Fig. 16. Comparing to not using UGW, the absorbed energy of LSA is reduced by more than 2 times using UGW.

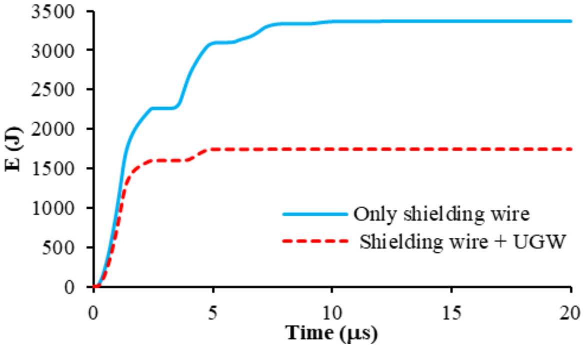


Fig. 16. Absorbed energy of LSA.

6.6 Lightning Current on UGW

When lightning strikes tower top with the lightning current value of 90 kA, the footing resistance is 10 Ω. Lightning currents on the UGW and on the footing resistances of the tower are shown in Fig. 17. The results show that the lightning current traveling on shielding wire and the footing resistance to ground and also on UGW wire, accounts for 20 % of the lightning current value. In this way, the lightning performance of transmission lines is improved due to voltage drop across the insulator during a lightning strike.

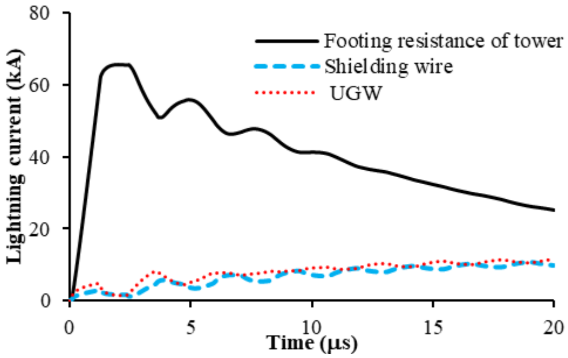


Fig. 16. Lightning current on UGW.

7. CONCLUSION

This paper has explained clearly the effect of the coupling factor on the insulator's voltage.. Simulation results show that using LSA coupling with UGW is an effective solution to both reduce outage rate of line and reduce the number of installed LSA. Using the UGW increases the coupling factor of the shielding wire and the phase conductors, especially the phases located away from these two wires. This reduced the impulse voltage on insulator when line by lightning strike and limits or eliminates the possibility of flashover on the insulation due to a lightning strike. Installing UGW will cause the coupling factor to be increased by up to 70%, which will significantly reduce the voltage applied to the insulator.

Using UGW reduces the outage rate of TL which is caused by lightning. The transmission outage rate using UGW is reduced by 1.5 times compared to the case without UGW and if adding 1 LSA the cutting rate is reduced by 2.4 times. Using UGW helps selecting LSA with softer ratings, reducing number of LSA to be used on a tower (hanging on one phase, instead of hanging on two or three phases). Hanging UGW coupling with LSA has effects on reducing BFR for the TL better than using two LSAs when the tower grounding resistance is low. Moreover, UGW reduces LSA's energy absorption, so smaller LSAs are cheaper.

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